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OLD PROBLEMS IN LOW-ENERGY KN PHYSICS AND PERSPECTIVES OPENING UP AT NEW MACHINES

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ABSTRACT

We survey the open problems in low-energy KN physics, in the perspective of using the new machines presently planned, such as the ϕ -factory DAΦNE at I.N.F.N. Nat. Labs. in Frascati (as a source of *tagged*, low-energy kaons) and the KAON Factory at TRIUMF (as a producer of intense, intermediate-energy kaon beams).

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1. INTRODUCTION.

The aim of this contribution is to review the state-of-the-art of both our experimental and theoretical knowledge of the low-energy KN physics, and to stress the importance of better information on several of its parameters, notably the KNY coupling constants and the KN sigma terms.

Our main motivation stems from the possibilities opening up in the next few years, when new machines such as DAΦNE and KAON will become operational. They will make possible again to perform systematic studies of KN interactions, whose importance was stressed in the past¹, in connection with the closing down of low-energy machines and/or kaon beam lines (particularly with the demolition of NIMROD and the closing of CERN beam lines); this left the remaining beam lines, at BNL and KEK, to carry all the load of the recent research with strange particles.

Now let us shortly describe the main, relevant features of DAΦNE and KAON, in order to elucidate their complementarity for such a systematic investigation.

DAΦNE (“Double Annular Φ-factory for Nice Experiments”) is the ϕ -factory, due to replace Adone at the Frascati National Laboratories of I.N.F.N., and has already been approved as part of the Institution’s five-year plan. Because of its high commissioning luminosity², its *two* interaction regions will be sources of $\simeq 436 K^\pm s^{-1}$, at a momentum of 126.9 MeV/c, with a momentum resolution of $\simeq 1.1 \times 10^{-2}$, as well as of $\simeq 303 K_L s^{-1}$, at a momentum of 110.1 MeV/c, with the slightly worse resolution of $\simeq 1.5 \times 10^{-2}$.

This will make possible to perform $K^\pm N$ experiments from the elastic threshold up to about 125 MeV/c and $K_L N$ experiments at 110 MeV/c with practically no background, since those from both π^\pm ’s and leptons are easy to eliminate at a trigger level: because the π^\pm ’s come *almost all* from events with three or more final particles, the former can be suppressed by momentum and acollinearity cuts, while the latter are completely eliminated by a momentum cut, which also eliminates collinear pions from $\phi \rightarrow \pi^+ \pi^-$.

The KAON (“Kaons, Antiprotons, Other hadrons and Neutrinos”) Factory design is an accelerator complex, recently approved by the Canadian Federal Government, which will use the existing TRIUMF H^- cyclotron as an injector³. Six charged-kaon channels are foreseen with momenta ranging from 0.4 to 21 GeV/c, and the intensities of the beams in the lowest momentum range below 800 MeV/c go from a few to about a hundred millions

K^- s⁻¹, K^+ beams being about twice more intense⁴.

Decays in flight limit the purity of fixed-target-machine kaon beams: to perform measurements at momenta below 400 MeV/c, one has to use moderators, which at the same time decrease the kaon intensity and increase the beam contamination at the final target. This contamination requires identification of the incoming particles either via additional TOF or Čerenkov apparatuses: thus the advantage provided by the high intensities has to be balanced against the higher costs of the experiments. This situation contrasts that at the ϕ factories, where the intensities are lower by orders of magnitude, but contaminations can be controlled without additional setups.

The coming in operation of KAON and DAΦNE will improve significantly our possibility of making low-energy KN experiments, both increasing statistics and covering in detail regions barely explored in the past: this will allow new, much more accurate analyses. Therefore in this contribution we want to discuss which phenomenological aspects of KN physics may benefit from the situation. For this purpose we shall briefly review the present status of the phenomenology and mention a number of problems which are still open.

2. THE STATUS OF PRESENT INFORMATION ON KN INTERACTIONS AT LOW MOMENTA.

The low-energy interactions for both K^+N and K^-N are described in terms of phase shifts. The amplitudes for the two sectors ($S = +1$ and $S = -1$) are related by analyticity and crossing; additionally, the regeneration amplitude is a linear combination of the two. In the following we shall give a picture of the situation of the phase shifts for each sector separately. It has to be observed that this information comes basically from the charged-kaon induced reactions: although it has occasionally been suggested to analyze simultaneously these data and the regeneration ones⁵, the statistical weight of the latter has been insufficient to provide more than a mere consistency check⁶.

Let us start with the $S = +1$ sector. Most K^+N data come from experiments performed more than ten years ago, excepting some higher-momentum polarization data coming from KEK. The low-energy region is described by S - and P -waves for both $I = 0, 1$ isospin channels: while K^+p scattering is pure $I = 1$, with a repulsive S -wave and a weak P -wave which starts being felt only in the higher-momentum range, K^+n scattering (whose extraction from K^+d requires a treatment of the three-body problem

for the Knp system) contains also an $I = 0$ amplitude, characterized by a small S -wave scattering length and a weak P -wave (as in the $I = 1$ channel).

The general behavior of the low-energy amplitudes is thus rather well understood⁷. Interactions of K^+ 's with the nuclear constituents correspond to a mean-free path of about 7 fm, so that they are sensitive probes of nuclear matter; in the last few years much debate has been given to the comparison of K^+ scattering on nucleons with that on nuclei (in particular on carbon), which led to the suggestive hypothesis of a possible swelling of nucleons in nuclei⁸. The present uncertainty on the relevant data does not allow sharp predictions, so that more precise information is necessary.

Turning now to the $S = -1$ sector, the most typical features of low-energy $\bar{K}N$ scattering are its large unphysical regions, which start at the $\pi\Lambda$ threshold for $I = 1$ and at the $\pi\Sigma$ one for $I = 0$, and extend to the elastic $\bar{K}N$ one. The importance of these regions is enhanced by the presence of both the P -wave $\Sigma(1385)$ and the S -wave $\Lambda(1405)$ resonances: the scattering amplitudes there have to be analytic continuations of the corresponding ones in the low-energy $\bar{K}N$ channels⁹.

The low-energy amplitudes are described by a partial-wave formalism which has to include: a) couplings between *all* the open channels, b) analyticity in the energy plane, and c) unitarity in all channels considered. The most common one is the K-matrix formalism¹⁰⁻¹², where one writes the partial-wave T -matrix \hat{T}_I^l as

$$(\hat{T}_I^l)^{-1} = (\hat{K}_I^l)^{-1} - i\hat{Q}^{(2l+1)} . \quad (1)$$

Here \hat{K}_I^l is a real Hermitian matrix, and \hat{Q} is the diagonal matrix of the c.m.s. momenta q_i (or a modification of the latter, analytic in the cut s -plane and having the same behavior at the thresholds). Several parameters are usually required to describe the low-energy region above *and* below threshold, leaving much too large a margin for ambiguities, given the quality of presently available data, unless the parameters are otherwise constrained by suitable theoretical arguments.

A little accounting shows that, even neglecting the weakly coupled $\pi\pi\Lambda$ channel, the formalism requires, for each coefficient of a power series in s for either \hat{K}_I^l or its inverse \hat{M}_I^l , three parameters for $I = 0$ and six for $I = 1$, or a total of 36 parameters to describe all channels up to order q^3 with S - and P -waves.

Note that the charge states of the same system have been counted as *one* channel: though the differences in threshold energies could be considered purely electromagnetic

effects, the situation is here more complex than in the πN case, even in the physical region. We have indeed $\omega_{\bar{K}^0 n} - \omega_{K^- p} = +8.13$ MeV, corresponding to a $p_L(K^-) = 90$ MeV/c, versus $\omega_{\pi^0 n} - \omega_{\pi^- p} = -3.79$ MeV: thus $\bar{K}^0 n$ threshold effects (cusps and/or dips) will be observable in the momentum region covered by the ϕ -factory kaons, and could provide valuable information on the interplay between electromagnetic and strong interactions in the K-matrix representation of the $\bar{K}N$ amplitudes.

Presently available low-energy data consist essentially of *integrated* cross sections, with extremely scarce angular distributions and polarizations, coming in only at higher energies; as mentioned above, this, and the limited statistics, do not allow to determine uniquely the parameters, and additional constraints are usually introduced.

As a typical example of this procedure one can mention the use of fixed- t dispersion relations¹⁰ (for symbols and conventions, see Ref. 9)

$$D^+(\omega) = D^+(0) + \sum_Y \frac{\omega R_Y g_Y^2}{\omega_Y(\omega - \omega_Y)} + \frac{\omega}{\pi} \int_{\omega_{thr}}^{\infty} \left[\frac{A^+(\omega')}{\omega'(\omega' - \omega)} - \frac{A^-(\omega')}{\omega'(\omega' + \omega)} \right] d\omega', \quad (2)$$

connecting the threshold amplitudes and the integrals over the unphysical region, entering the last term (given by fits to the low-energy data), to data on real and imaginary parts of the amplitudes at higher energies.

Good knowledge of the real parts is essential in making such constraints tight, calling in turn for high-quality measurements of elastic cross sections in the Coulomb-nuclear interference region: the accuracy of available data has till now limited the use of these constraints to $t = 0$, where the imaginary part of the amplitude is provided by the optical theorem. Drastic improvements over the quality of the data used for amplitude analyses⁷ (both $d\sigma/d\Omega$ and polarization P) are required to extend them also to $t \neq 0$.

In this context one has to remark that the validity of dispersion relations is related to that of microcausality at short distances; the use of dispersive constraints in data analysis may then weaken the significance of the tests on the above validity. Therefore the availability of new, accurate, low-energy data should be regarded as an essential contribution to an unbiased understanding of the basics of fundamental interactions.

A general feature of all the parametrizations is a strongly absorptive interaction in both isospin channels. However, the detailed structure of the amplitudes, particularly in the unphysical region, is far from being determined, mainly due to the low statistics of the experiments performed up to now on inelastic production of these low-mass systems¹³.

3. THE STILL UNANSWERED PROBLEMS OF LOW-ENERGY KN PHYSICS.

The uncertainties discussed in the previous section, on the determination of the low-energy $\bar{K}N$ and KN amplitudes, reflect on uncertainties in the evaluation of a number of quantities, which are fundamental to our understanding of strong-interaction physics in the strange-particle sector. In particular we are referring to the KNY coupling constants, to the σ -terms, and to the still open puzzle posed by the energy shift and the width of the X-ray lines of kaonic hydrogen.

Coupling constants were once considered fundamental, or studied as tests of $SU(3)_f$ symmetry; they have regained status as sensitive tests of the structure of the *explicit* chiral-symmetry breaking of QCD¹⁴, via their deviations $\Delta_{KNY}(0)$ from Goldberger-Treiman relations, defined by

$$\sqrt{1/2}(M_N + M_Y)G_A^{YN}(0) = f_K g_{KNY} + \Delta_{KNY}(0) , \quad (3)$$

and strongly dependent on the nature and parameters of this breaking in QCD¹⁵.

Note that the most advanced analyses¹⁶ still yield errors of order unit on $g_{KNY}^2/4\pi$, *one order of magnitude* larger than errors in the πN case! To reach definite conclusions, one needs thus one order of magnitude improvements¹⁷ on the determination of the couplings: due to the cancellations involved in the dispersive integrals, this requires even better improvements in the actual data. For the $KN\Sigma$ coupling (the smaller and more uncertain of the two) K_S regeneration in hydrogen is the best source of information, directly giving (through isospin symmetry) the charge-odd combination of $K^\pm n$ amplitudes required for the integrands, and thus eliminating part of the above-mentioned cancellations, while at the same time dispensing us from the uncertainties related to the neutron-amplitude extraction from $K^\pm d$ data¹⁸.

It is also worthwhile mentioning that deuterium scattering data *do not exist at all* below a momentum of about $400 MeV/c$, and one has to replace them with extrapolations (with inherently larger errors) over a quite sizeable energy interval. Scattering data on deuterium are also interesting *per se*, as a testing ground of multichannel, three-body calculations.

A second problem, related both to the nature of the chiral-symmetry breaking and to the structure of the baryon octet wavefunctions, is the determination of the so-called σ -terms, proportional to the elastic, forward scattering amplitudes for zero four-momentum

kaons. Their values can be extracted in the most economical way using the values for the amplitudes at zero laboratory-energy, at momentum transfers $t \leq 0$ obtainable from fixed- t dispersion relations¹⁹.

Amplitudes at zero laboratory-energy do not have any special theoretical significance in themselves: it is only because the Cheng-Dashen point for KN -scattering amplitudes, $t = 2m_K^2$, $s = u = M_N^2$, lies in the t -channel unphysical region, that one is forced to construct a “modified Cheng-Dashen technique”, employing zero-energy amplitudes, to get at the KN σ -terms. These, and in particular their $I_t = 0$ part

$$\sigma_{KN}^{(0)} = \frac{m_s + m}{m_s - m} \frac{1 + y}{1 - y} [\langle N | -\frac{3}{4} H_8(0) | N \rangle] + O(\frac{m_d - m_u}{m_s - m}) , \quad (4)$$

are an extremely sensitive and direct measurement of the scalar, strange-quark density in the nucleon, measured by the ratio

$$y = \langle N | \bar{s}s | N \rangle / \langle N | \frac{1}{2}(\bar{u}u + \bar{d}d) | N \rangle . \quad (5)$$

The above σ -term is a much more direct indication of the value of y than the πN one

$$\sigma_{\pi N} = \frac{m}{m_s - m} \frac{1}{1 - y} [\langle N | -3 H_8(0) | N \rangle] , \quad (6)$$

where it is hard to separate the strong dependence on y from the equally strong one on the light-quark mass ratio m_s/m .

The ratio y has been the subject of a recent, lively theoretical debate²⁰ (mostly based on model-dependent assumptions), with wide-ranging implications, from OZI-rule violations in scattering and production of hadrons, through the validity of lattice approaches to baryon structure and spectroscopy, to the equation of state of dense baryonic matter, with the enticing possibility of “kaon condensation” in primordial baryogenesis, dense neutron stars, and relativistic heavy-ion collisions²¹.

Employing t -channel unitarity and analyticity, plus the hypothesis that the S -wave dominates this channel at low values of t , the on-mass-shell, zero-energy amplitudes have been connected to the σ -terms, via the phases $\phi_I(t)$ of the isospin- I , t -channel $\bar{N}N \rightarrow \bar{K}K$ amplitude, related to the S -wave meson-meson ones via coupled-channel unitarity in an N/D representation¹⁹, and derived a relation of the form

$$D_I^{(+)}(t) = \frac{2\sigma_{KN}^{(I)}}{f_K^2} \frac{P_I(t)}{P_I(2m_K^2)} \exp\left[\frac{t}{\pi} \int \frac{\phi_I(t') dt'}{t' - t}\right] + \text{Born term contributions} , \quad (7)$$

where $P_I(t)$ is a suitably smooth function of t , analytic in the t -plane cut from $t_L < 0$ to $t = 4m_K^2$. By dividing the zero-energy amplitudes (obtained from dispersion relations) by the Omnès function in eq. (7), and subtracting the Born terms, one extrapolates this representation to $t = 2m_K^2$ to extract the $I_t = 0$ σ -term, and from it the ratio y .

In contrast with the small absolute uncertainty of the method when applied to πN -amplitudes^{19,22}, its application to the KN case carries an *intrinsic* uncertainty of the order of 100 MeV for both $K^\pm N$ σ -terms, which could be adequate to discriminate between at least some of the existing, model-dependent predictions²⁰, were not the errors coming from the data several times larger^{19,23}, and indeed comparable with the estimates themselves. A definite answer to the σ -term problem, *both* for the KN and the πN systems, could thus come only through a drastic reduction in the errors of the first one, extremely sensitive to those on the low-energy and unphysical $\bar{K}N$ regions²³, due to large cancellations in the dispersive integrals and between these latter and the Born terms.

Another problem, which for a long time has puzzled baryon spectroscopists, is the nature of the $\Lambda(1405)$, shifting with times from the S -matrix language (CDD pole, $\bar{K}N$ bound state, or resonance?) to the quark-gluon one (qqq baryon, $\bar{K}N$ bound state, multi-quark or hybrid state?). Indeed even its correct reproduction remains an outstanding problem in quark-model phenomenology²⁴.

The state can be directly observed (and has indeed been seen¹³) only in $\Sigma\pi$ (and possibly in $\Lambda\pi\pi$) inelastic production: the determination of its coupling to the channel $\bar{K}N$ requires an *extremely stable* extrapolation of the parametrization for the threshold-region into the unphysical one, possible only with much smaller error corridors and more stringent analyticity constraints than those presently available²⁵.

The $\Lambda(1405)$ nature reflects on the probabilities for radiative capture at threshold (the “strange” analogues of the Panofsky ratio in the πN system) as well: present measurements are just above observability²⁶ (mostly because of the extremely high backgrounds due to the pion contamination of the beams), and therefore unable to decide between different, if not conflicting, theoretical expectations²⁷.

The high purity of the ϕ -factory as a kaon source makes it an ideal environment for this kind of physics.

Last, but not least, we wish to mention the still open mystery of kaonic hydrogen: the three experiments performed up to now on this system²⁸ have collected a total of only a few tens of events *interpreted* as atomic K -lines, above backgrounds orders of magnitude

larger. Even their identification as *bona-fide* kaonic-hydrogen spectral lines is open to questioning²⁹. Also, to the best of our knowledge, all models purported to reproduce them conflict either with $\bar{K}N$ amplitude analyses or with simple, quantum-mechanical pictures of absorptive processes: thus these models either failed to solve this mystery, or were able to explain the data only at the price of highly non-smooth or even unphysical energy behaviors of the amplitudes³⁰.

An experiment, planned to clearly identify and measure energies and widths of the K^-p (and K^-d) K -lines, could either eliminate the mystery or open the way to new and unforeseen physics in this very-low-energy domain of the strong interactions.

4. A SKETCH OF AN EXPERIMENTAL AND THEORETICAL PROGRAM FOR KN PHYSICS AT THE NEW MACHINES.

This last section of our review will be covering what we believe are the programs to be carried out, both by the experimentalists working at the new machines and by the theorists in order to fully exploit the data these machines will be producing.

In 1990, at the Vancouver “Workshop on Science at the KAON Factory”, we presented a list of experiments we then thought could, and ought to, be carried on *only* at such a facility³¹. The new possibilities, opening up at a *suitable* ϕ -factory such as DAΦNE³², force us to slightly revise that list.

Its first item was “a dedicated, low-energy ($p_L \leq 300$ MeV/c) K^-p or K^-d ” scattering “experiment with the cleanest beam-line afforded by present-day technology”: probably for $p_L \leq 125$ MeV/c a *dedicated* detector at the ϕ -factory DAΦNE can win over a fixed-target experiment, due to the *extreme* cleanliness of the former in this momentum range, even despite its low kaon-production rate. A possibility we did not mention was that of doing experiments with polarized targets: fixed-target machines are indeed the *only* place where these measurements can be performed. The latter, essential to any good amplitude analysis, have been up to now unavailable for momenta below about 800 MeV/c. Note in this respect that DAΦNE can produce about 3×10^6 K^-p interactions in a typical apparatus³² in a “Snowmass year” (*i.e.* 10^7 s) of experimentation, enough to measure angular distributions in all channels, and also polarizations, but the latter only for the self-analyzing, final-hyperon states.

Second item on that list was a “good quality K_S^0 -regeneration experiment on hydrogen (and deuterium) with an intense, low-momentum K_L^0 beam”: here DAΦNE can help

at very low momenta (110 MeV/c only), measuring *tagged* K_S^0 regenerations (together with *all inelastic channels*) in the same apparatus used to measure K^- (and K^+) interactions with hydrogen (or deuterium, changing the gas filling the “target” fiducial volume), again with “yearly” rates of the order of 10^6 events.

The third item was “a kaonic–hydrogen and deuterium experiment”: Shimoda should see presented the first results coming out of the new Japanese experiment, which hopefully should solve (or reopen?) the mystery. Undeniably, KAON fluxes shall make statistics even better, and thus offer a further, stringent constraint on KN amplitude analyses, fixing the K^-p and K^-d scattering lengths via the energy shifts and widths of the atomic $1s$ levels.

Last item on the list was “an elastic–scattering experiment in the Coulomb–nuclear interference region to map $\rho = D/A$ ”, the real–over–imaginary–part ratio, “over reasonably small energy steps”, where of course the wide momentum ranges that will be provided by KAON should prove invaluable.

We wish to add now to this list the remark that a DAΦNE detector dedicated to kaon experiments on gaseous H_2 and D_2 can continue its active life, without substantial changes, to measure K^+- , K^- , and K_L^0 –interactions on heavier gases as well (He , N_2 , O_2 , Ne , Ar , Kr , Xe), exploring not only the properly “nuclear” aspects of these interactions, such as the aforementioned nucleon “swelling” in nuclei⁸, but also producing $\pi\Sigma$, $\pi\Lambda$ and $\pi\pi\Lambda$ systems with invariant masses in the $\bar{K}N$ unphysical region, with statistics substantially higher than those now available¹³, due to the $\simeq 4\pi$ geometry allowed by a colliding–beam–machine detector.

All these experiments will provide data of the same quantity and quality now available only for the πN system: theoretical tools for their analysis must thus be improved as well, to meet the standards required by this, long awaited for, “forward leap” in the quality of the KN data. Tools of just this level have since long been provided for πN amplitude analysis by the so–called “Karlsruhe–Helsinki collaboration” headed over the years by Prof. G. Höhler³³; their software can not be straightforwardly “imported” to do KN amplitude analyses, mainly because of the complicated analytic structures of the low-energy $\bar{K}N$ strong–interaction amplitudes. Much for the same reason, the dispersive treatment of Coulomb corrections developed at NORDITA³⁴ can not be immediately transferred to the strange sector. It has to be recalled that the old data were *almost always* analyzed using, for these corrections, the old, approximate formula of Dalitz and Tuan³⁵, which may be inapplicable to a strongly absorptive interaction close to threshold²⁹.

Since the basic principles on which both approaches are based have to hold also for the KN system, as for the πN one, it remains for us to work out the details of a partial-wave-analysis procedure, applicable to a system strongly absorptive at threshold such as the $\bar{K}N$ one, and possessing *ab-initio* the following requirements: i) consistency with both fixed- t and partial-wave dispersion relations; ii) crossing symmetry (and isotopic-spin symmetry as well, to describe *simultaneously* charge-exchange and regeneration data); iii) analyticity in t beyond the Lehman ellipses, with the *correct* low-mass, t -channel-cut discontinuities given by the $\pi\pi$ cut; iv) a *complete* treatment of Coulomb corrections.

Both of us have in the past carried out parts of this program (as many others have also done more or less at the same epoch), but only for *limited purposes*, such as extrapolations either to the hyperon poles¹⁶ or to the Cheng-Dashen point¹⁹, or studies of Coulomb effects at threshold²⁹: what remains to be done is a merging together of all these techniques into a “global” analysis, on which work is presently under way.

In this perspective we have advanced the proposal to I.N.F.N. for a program of extensive collaboration, code-named KILN (for “Kaon Interactions at Low energies with Nucleons”), which has already received an initial, and thus limited, financial support.

Participation in this collaboration is highly welcome, and we take this occasion for calling upon all theorists which have been or wish to be active in this still open and very much alive (despite greatly exaggerated rumors on the contrary³⁶) field of particle physics.

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 36. The same also happened to Mark Twain, from which we took the liberty of borrowing the pun.